
Pbar Stacking Report

Dave McGinnis
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Outline

- Purpose
 - Investigate low pbar stacking rates in FY04
 - not including the AP2-Debuncher aperture work
- Investigation of sub-systems
 - Debuncher Momentum cooling
 - RF systems
 - Stacktail Momentum Cooling
 - Transfers between the Debuncher and Accumulator
 - Transverse Debuncher cooling
 - Transfer line between Debuncher to Accumulator
- Conclusions
- Proposed Plan of Work

FY04 Goals

- Goal

- Zero Stack Stacking Rate 18×10^{10} pbars/hr
 - Beam on target 5.0×10^{12} protons per cycle
 - Production 17×10^{-6} pbars/proton
 - Cycle time 1.7 sec

- Achieved

- Zero Stack Stacking Rate 12.7×10^{10} pbars/hr^{*}
 - Beam on target 5.2×10^{12} protons per cycle
 - Production 15×10^{-6} pbars/proton
 - Cycle time 2.2 sec

- Difference

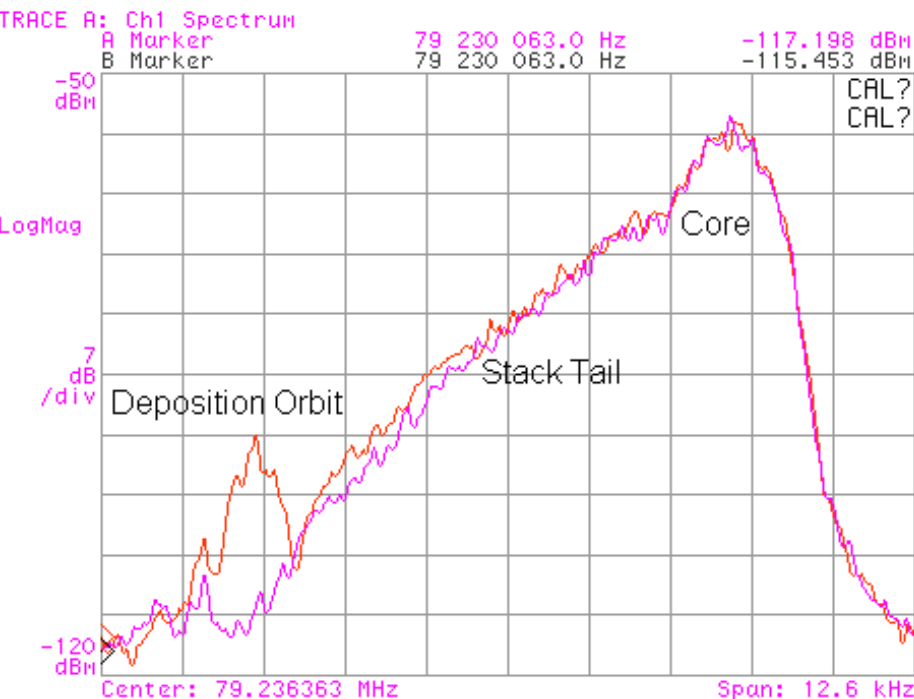
- Zero Stack Stacking Rate down 29%
 - Beam on target up 4%
 - Production down 12%
 - Cycle time up 29%

^{*}Averaged over the 10 stores with the highest initial luminosity

Pbar Cycle Time

- Initial focus on reducing the cycle time was spent looking at the Stacktail deposition orbit
- Beam must be cleared off the Stacktail deposition orbit before next beam pulse.
 - The more gain the Stacktail has, the faster the pulse will move.

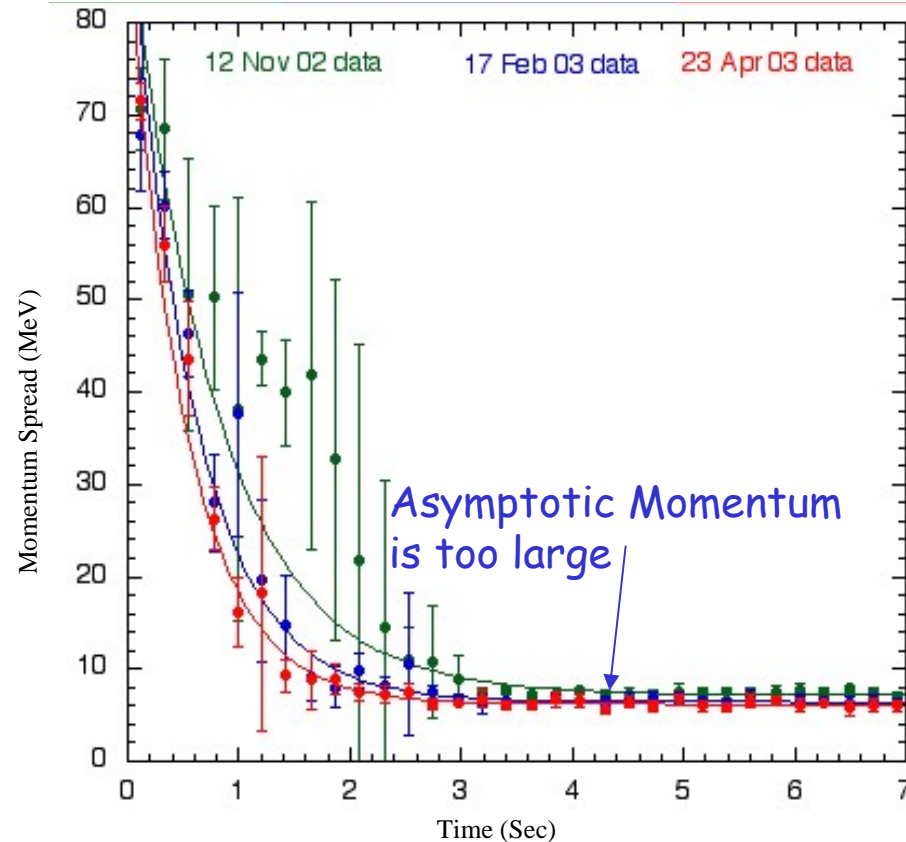
Accumulator Longitudinal Spectrum



- The Stacktail gain is limited by
 - System instabilities between the core beam and the injected beam
 - Transverse heating of the Stacktail on the core
- As the stack gets larger
 - The instability feedback path grows stronger
 - The core transverse cooling gain is reduced
- The gain of the Stacktail must be turned down to compensate
- The cycle time must increase for the lower Stacktail gain
- For a given Stacktail gain, the larger the momentum spread of the injected pulse, the longer it takes to clear the pulse from the Stacktail Deposition orbit.
 - The momentum spread coming from the Debuncher is too large.
 - Bunch length on target
 - Debuncher Cooling rate
 - Debuncher asymptotic momentum

Debuncher Momentum Cooling

- The 4-8 GHz Debuncher momentum cooling systems have enough gain to bring the momentum spread down in 1.5-1.7 secs.
- The momentum spread exiting from the Debuncher is limited by the asymptotic momentum spread.
- A large contribution to the asymptotic momentum was thought to be the result of dispersion in the Debuncher Momentum cooling notch filters.
- By reducing the Debuncher Momentum Cooling Notch filter dispersion by 33%, it was thought that the Stacktail gain could be lowered by 33% and would permit the zero stack cycle time to be lowered from 2.4 sec to 1.7 sec

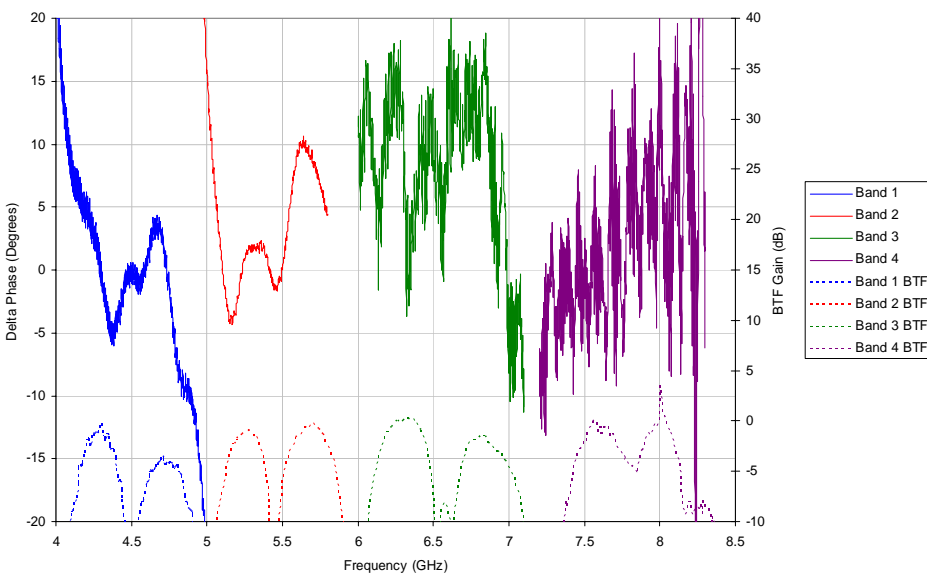


Debuncher Optical Notch Filters

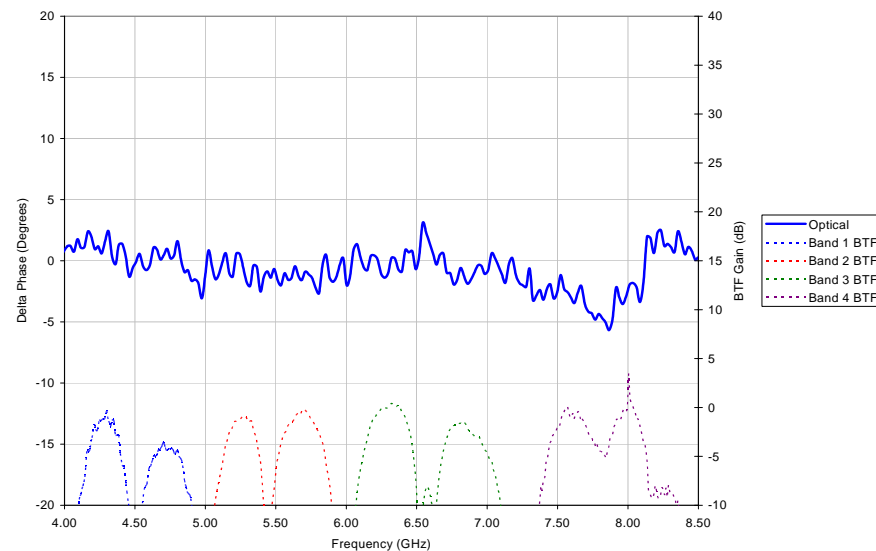
- Initial pass on reducing dispersion in the Debuncher notch filters was attempted by building better equalizers for the BAW delay lines for each of the 4 bands
 - Tolerances in building microwave strip-line filters limited the amount of dispersion that could be equalized
- Next step was to build optical notch filters
 - Factor of 3-4 lower in dispersion than Bulk Acoustic Wave filters
 - More difficult to implement than BAW filters because all 4 bands have to be channeled into a single optical filter and then split out separately again after the filter.
 - Optical filter was installed during the March '04 short shutdown

Bulk Acoustic Wave filters

Notch location

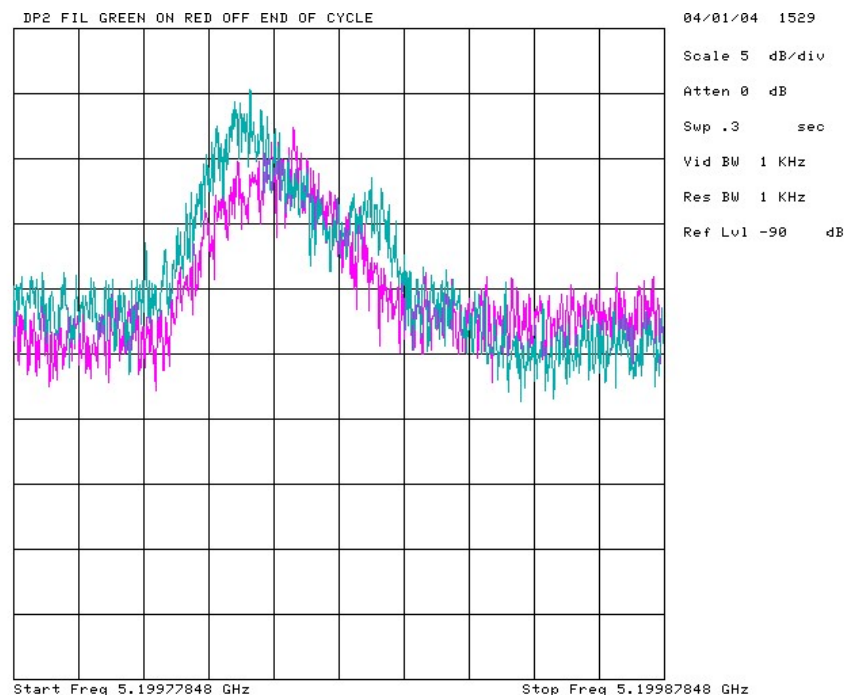
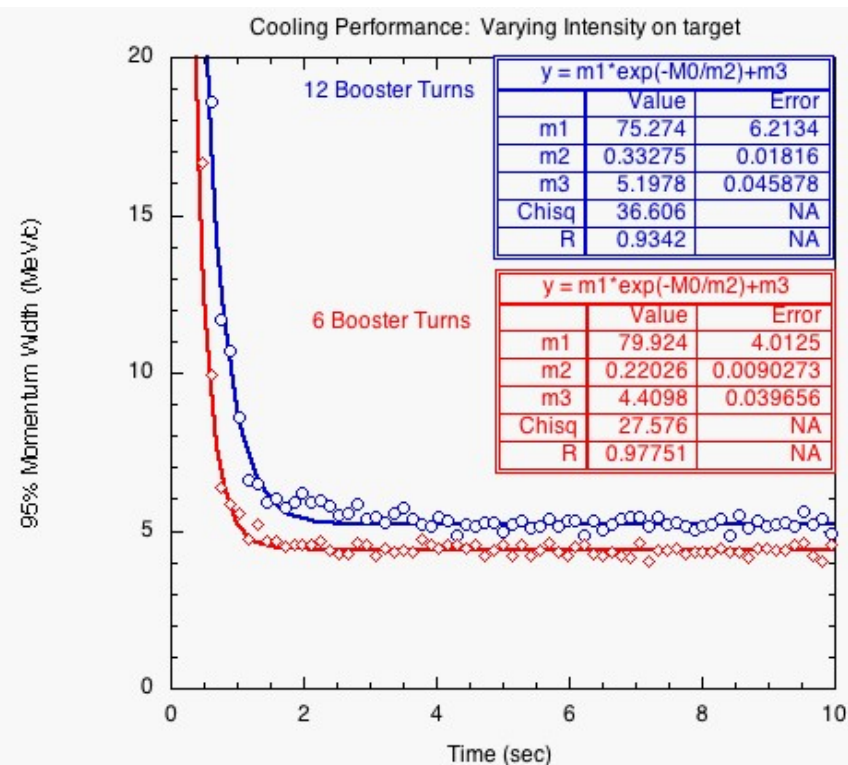


Optical filters



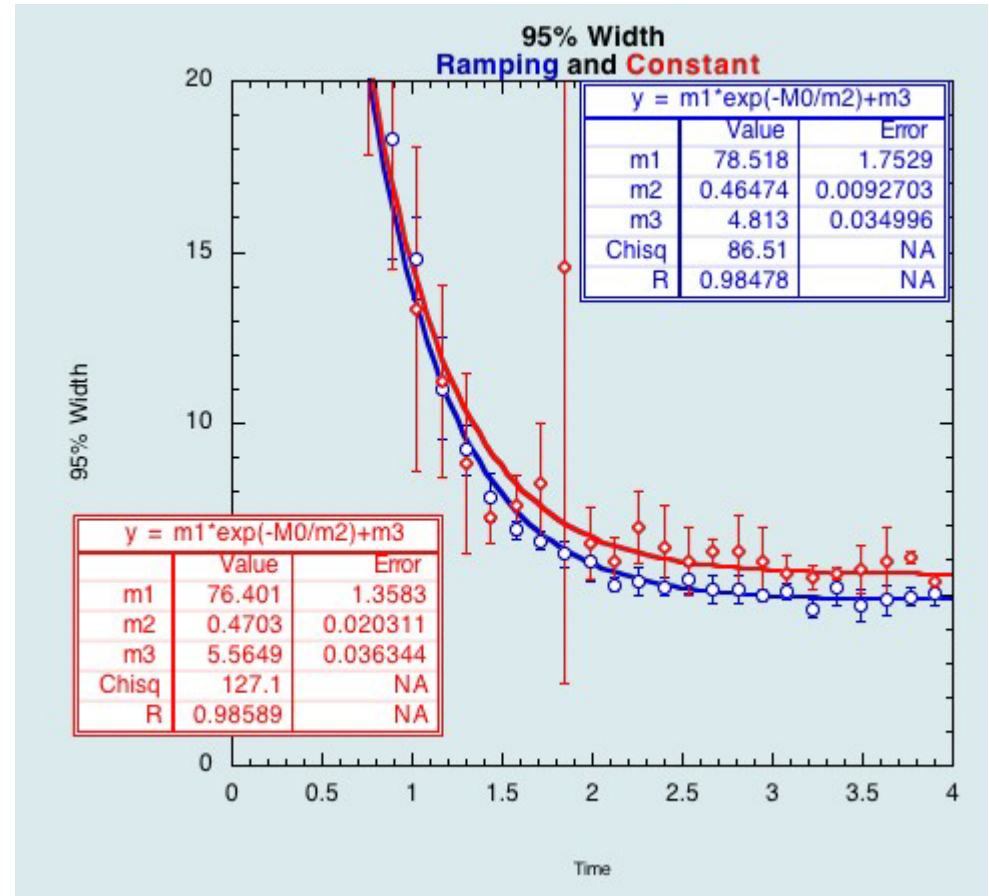
Optimum Gain in Debuncher Momentum Cooling

- Optical Filters reduced asymptotic momentum spread from above 8 MeV to about 6 MeV
- Subsequent measurements showed that the asymptotic momentum spread was a function of the amount of beam injected into the Debuncher
- Further measurements showed that the Debuncher Momentum cooling system was close to optimum gain



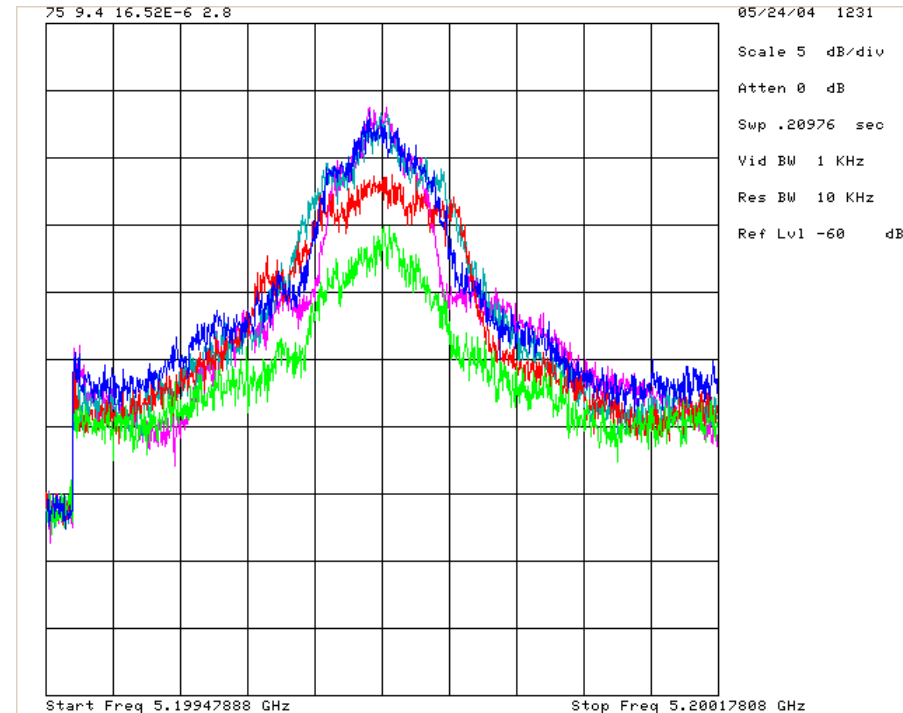
Momentum Cooling Gain Ramping in the Debuncher

- Gain ramps were introduced into the Debuncher Momentum Cooling system
 - Gain was reduced as momentum spread decreased (as particle density increased)
 - Gain ramping decreased the momentum spread to below 5 MeV



Static Decrease in γ_t in the Debuncher

- Bunch Rotation done during the first tens of milliseconds of the stacking cycle. Bucket height for bunch rotation is inversely proportional to $\eta^{1/2}$
- Stochastic cooling is done during the remaining 1.8 seconds of the stacking cycle. The error signal fed into the momentum cooling system is proportional to η .
- Ideal case would be to ramp γ_t down during cooling cycle
 - Under investigation
 - Power supply control, orbit control, tune control are issues
- Tried a static increase in η from 0.006 to 0.0075
 - Trade-off of bunch rotation bucket height vs large frequency spread for Debuncher Momentum cooling
 - Marginal results
 - Not fully explored



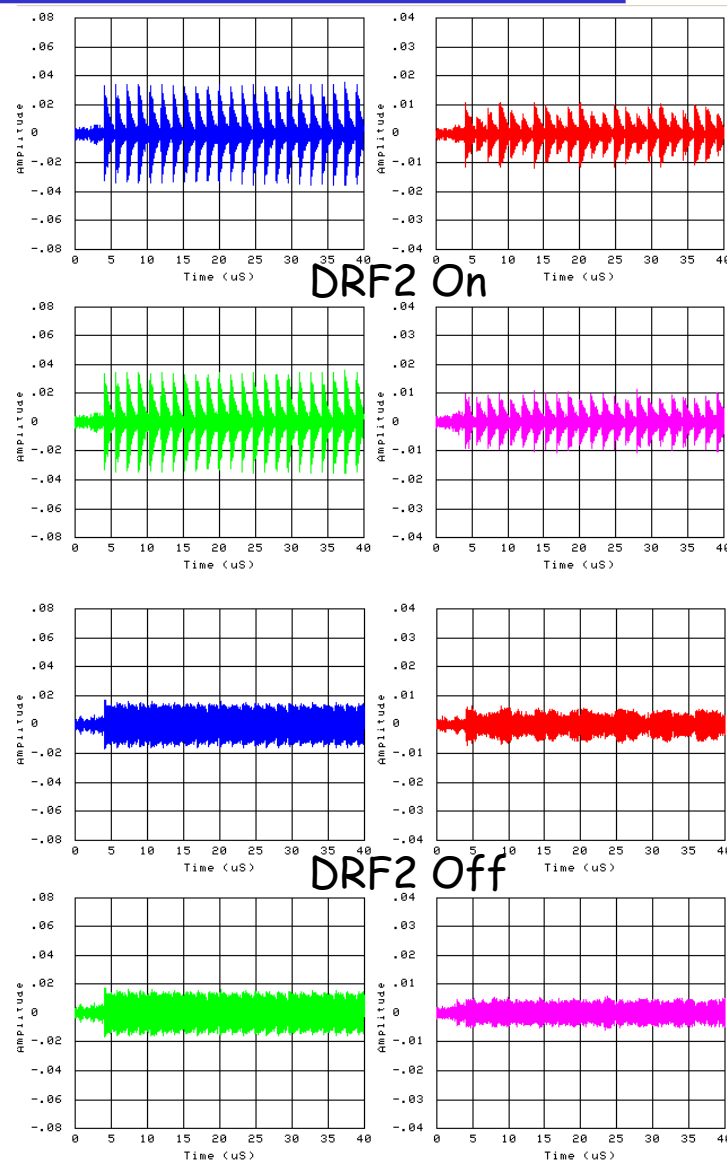
Debuncher Longitudinal Schottky after bunch rotation

Magenta Trace with small η

Blue Trace with increased η

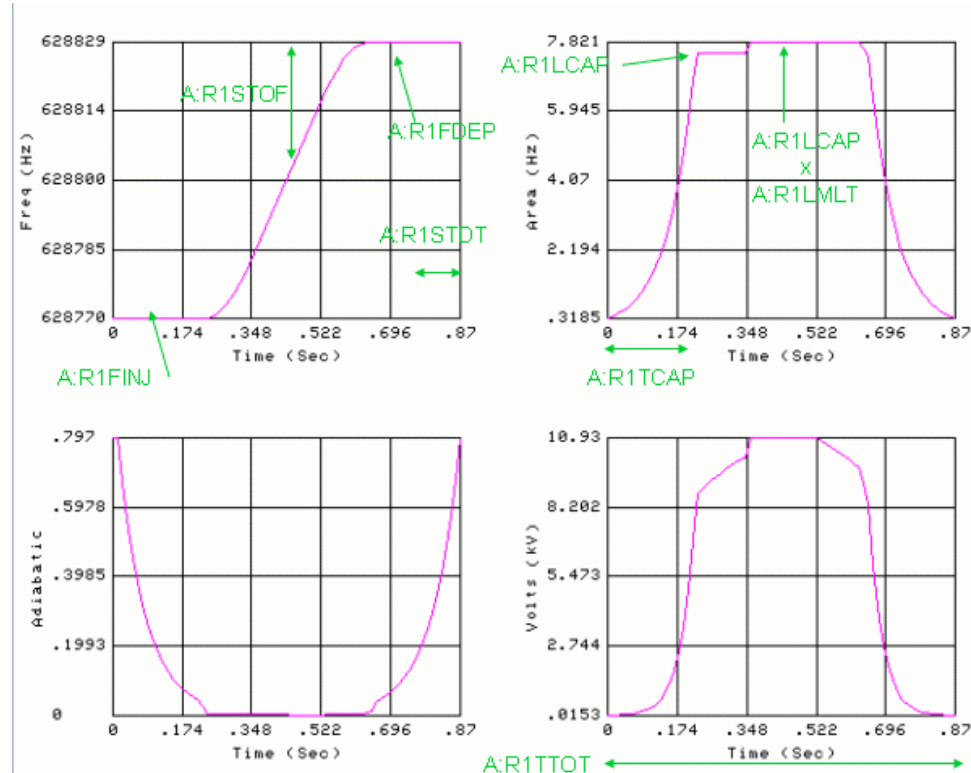
Gap Preserving RF in the Debuncher

- The Debuncher has a larger circumference than the Accumulator
- A 220 ns gap in the Debuncher beam is created with a barrier bucket (DRF2). This gap is large enough to accommodate the difference in circumference between the Debuncher and Accumulator and kicker rise and fall times.
- The voltage of DRF2 outside of the barrier bucket is supposed to be zero so that a rectangular phase space distribution will be transferred to the Accumulator.
- Recent measurements using the new TBT system for injecting pbars into the Accumulator has shown that there is a large bunching of the beam by DRF2 outside the barrier bucket.
- This bunching will result in a longitudinal emittance blowup when the beam is transferred to the Accumulator
- A new arbitrary waveform generator is being built for DRF2 and will be operational by the end of the shutdown.
 - This system can be tuned using the new Accumulator TBT



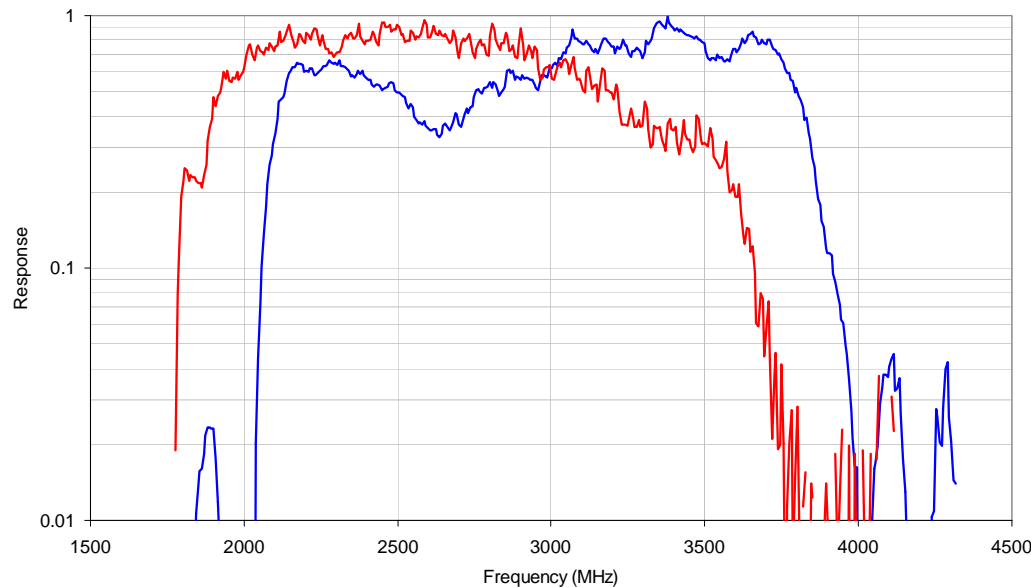
New ARF1 Curves Developed

- ARF1 is the RF system that decelerates beam from the injection orbit of the Accumulator to the deposition orbit of the Stacktail in the Accumulator.
- A new algorithm was developed for the ARF1 curve in which the low energy bucket edge of ARF1 is held at a constant energy when the bucket gets close to the Stacktail deposition orbit
- The curve is parameterized by 8 tunable ACNET parameters
- The curves can also be momentum selective which will be needed when NUMI comes into operation



Stacktail Bandwidth Adjusted

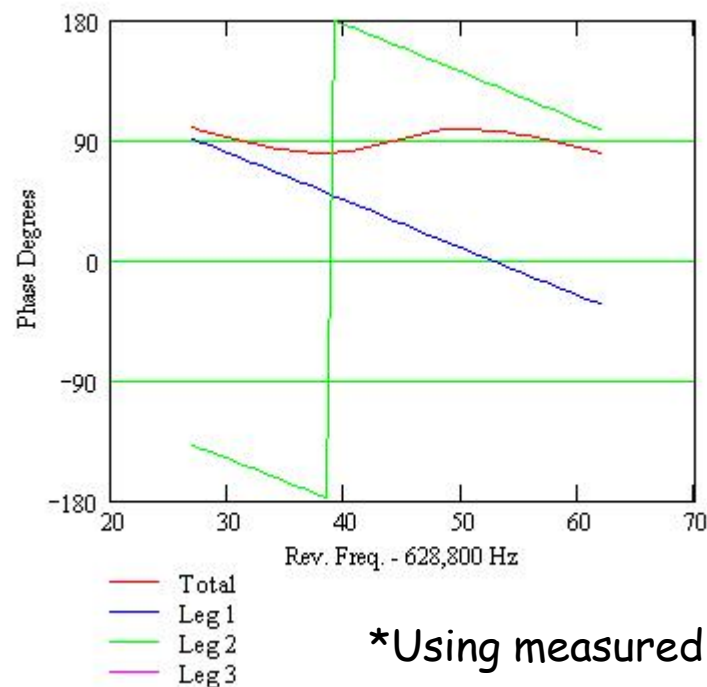
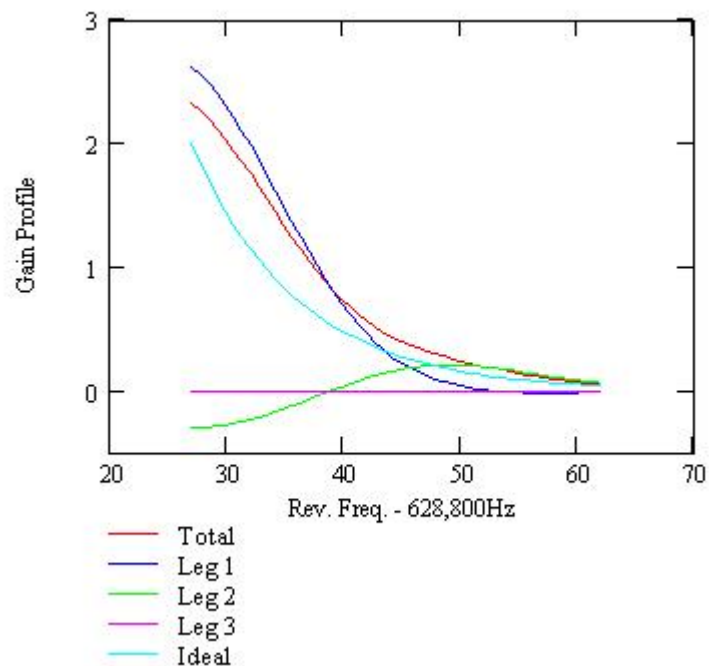
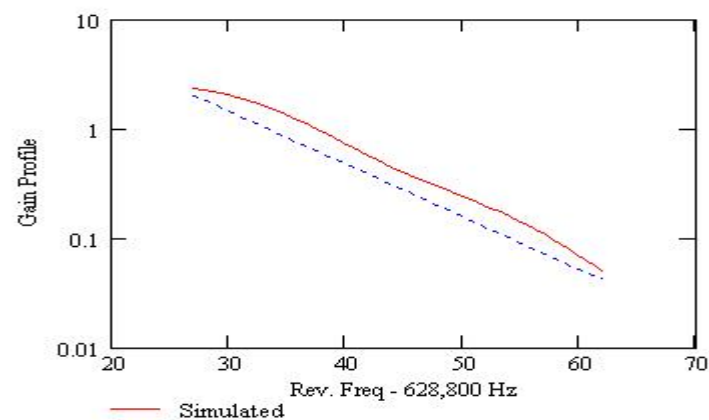
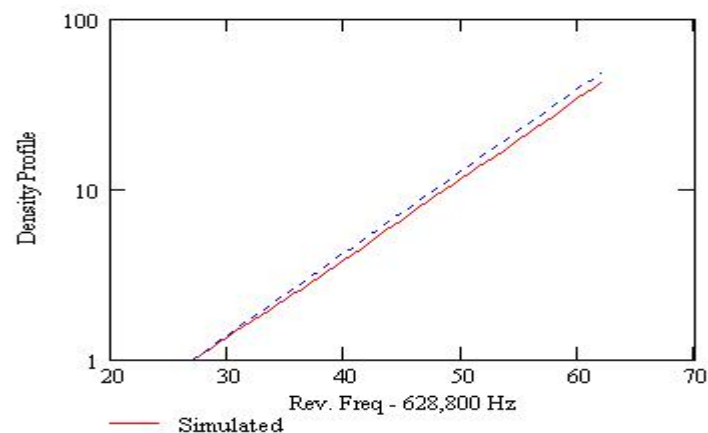
- The 2-4 GHz Stacktail pickups have sensitivity well below 2 GHz (to about 1.5 GHz)
- The initial BAW delay lines for the Stacktail notch filters cutoff sharply at 2 GHz
- An attempt was made to increase the Stacktail bandwidth by replacing the BAW delay lines with BAW delay lines that could reach lower frequency (1.5 GHz)
- Replacement yielded little or no gain because upper frequency band was lowered.



StackTail Phasing

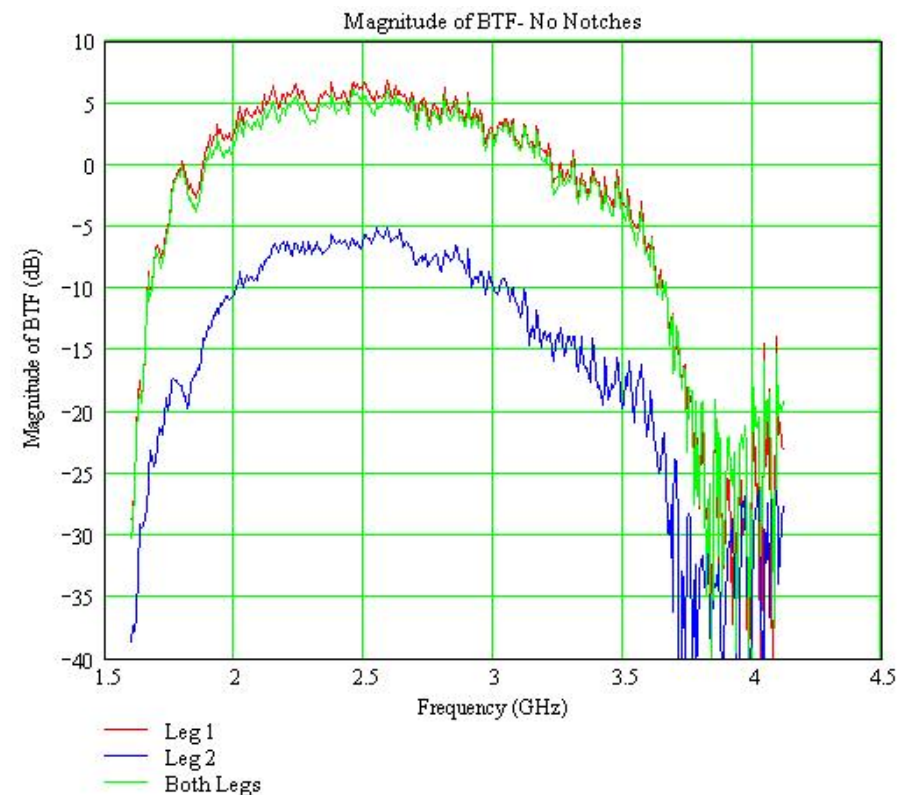
- Beam transfer function measurements were done with the beam placed on at revolution frequencies of 628,840 Hz (very close to the Leg 2 pickup) and 628,850 Hz
 - Beam was scraped to a width of 2Hz and scrapers were left in to ensure that beam width stayed at 2Hz
 - Fan-in and Fan-out were phased with very little changes made.
 - Trunk Beam transfer functions were made for all three legs independently.
 - Long leg of notch filters were left out for all legs
 - Saturation of amplifiers was checked by adjusting the network analyzer power and the trunk gain independently
- Using the actual beam transfer function measurements at 628,840 Hz, the theoretical Stacktail profile was determined by integrating the static Fokker-Plank equation.
 - with no phase shifter changes in the legs
 - With a gain slope of 9Hz
 - With notches at L1 = 628,873Hz, L2=628,887Hz, Trunk=628,887Hz
- The profile determined from the measured BTFs can support a static flux of 29.5 mA/hr

Fokker-Plank Integration Results*



*Using measured BTFs

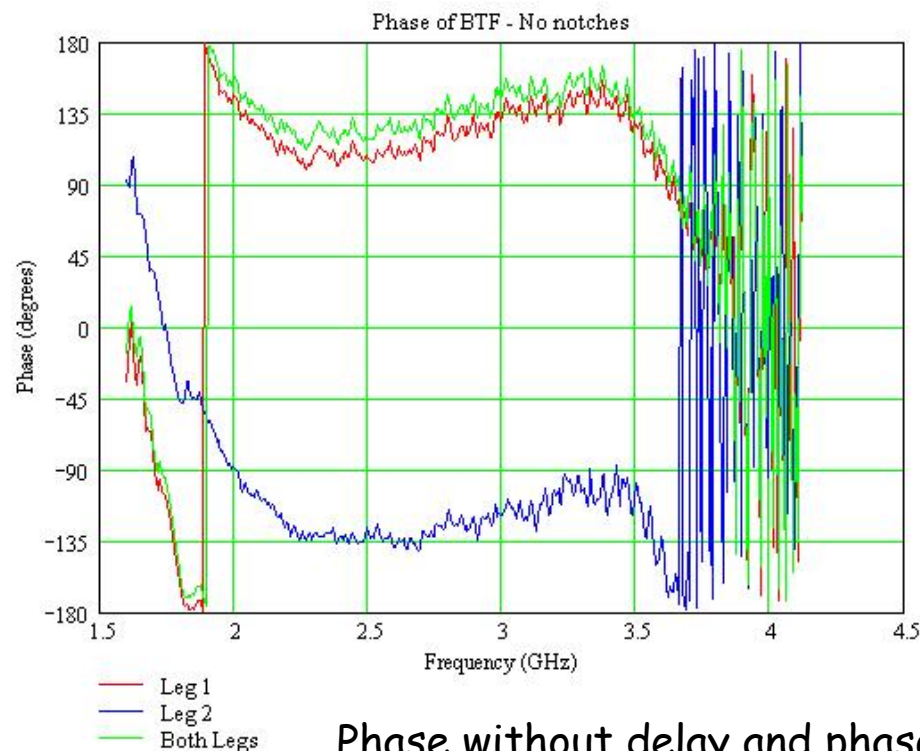
Magic Numbers at 628,840 Hz with No Notch Filters



Leg1 at 628,840 Hz

Delay = -26 pS

Phase = -149.5 degrees



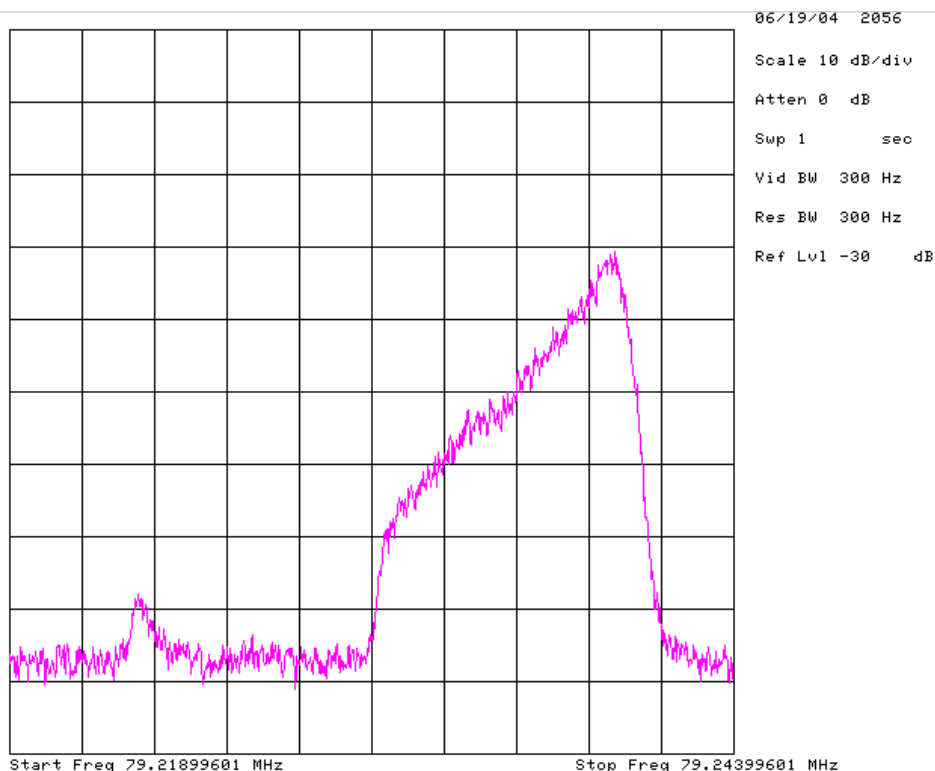
Phase without delay and phase intercept removed

Leg2 at 628,840 Hz

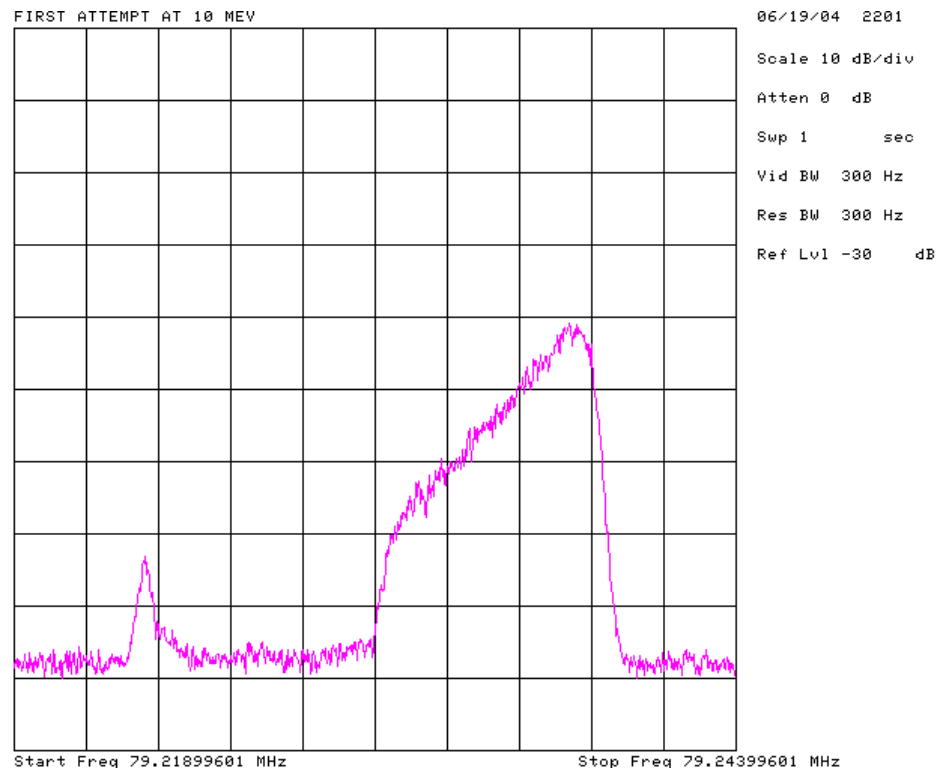
Delay = -47 pS

Phase = 75 degrees

Stacktail Profile with 9 Hz Slope



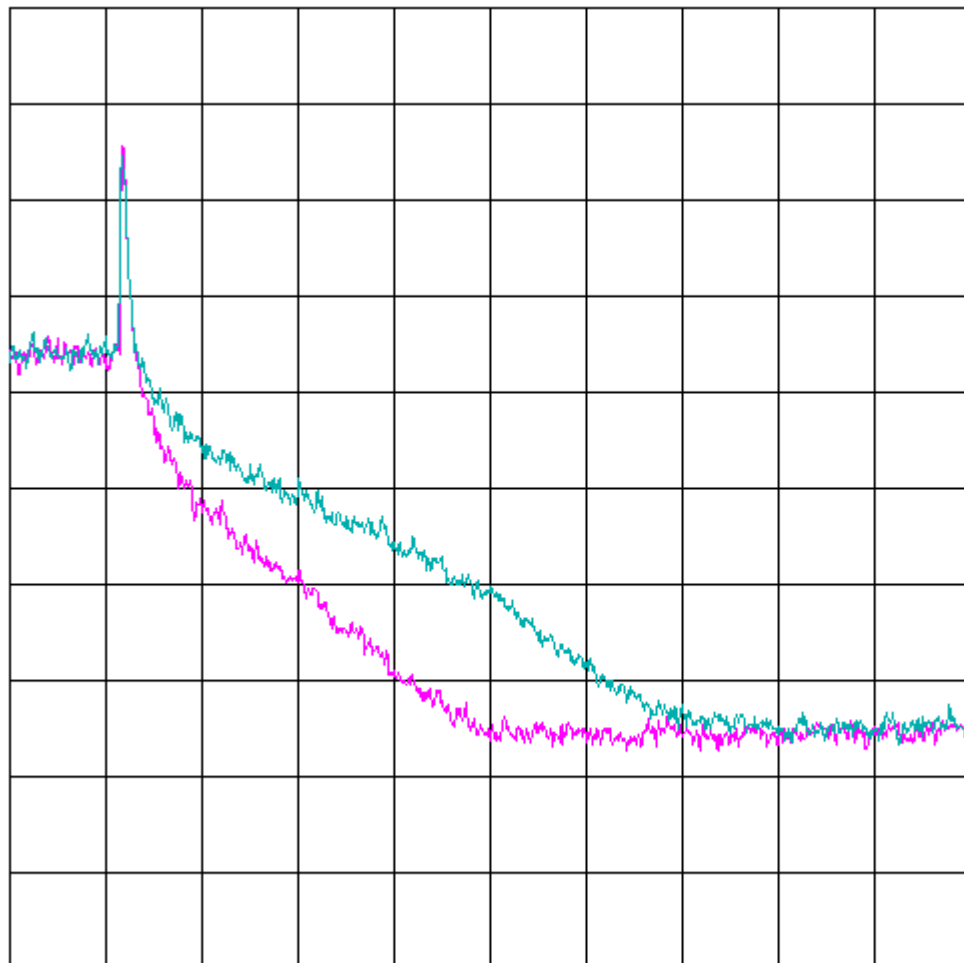
Profile Before Changes



Profile After Changes

Clearing Beam off the Stacktail Deposition Orbit

SP12 SCH WITH GAIN AT 10.5 DB



06/19/04 2245

Scale 5 dB/div

Atten 0 dB

Swp 3 sec

Vid BW 30 Hz

Res BW 10 KHz

Ref Lvl -69 dB

- With no core in the Accumulator, the rate at which the Stacktail moves beam off the deposition orbit was measured

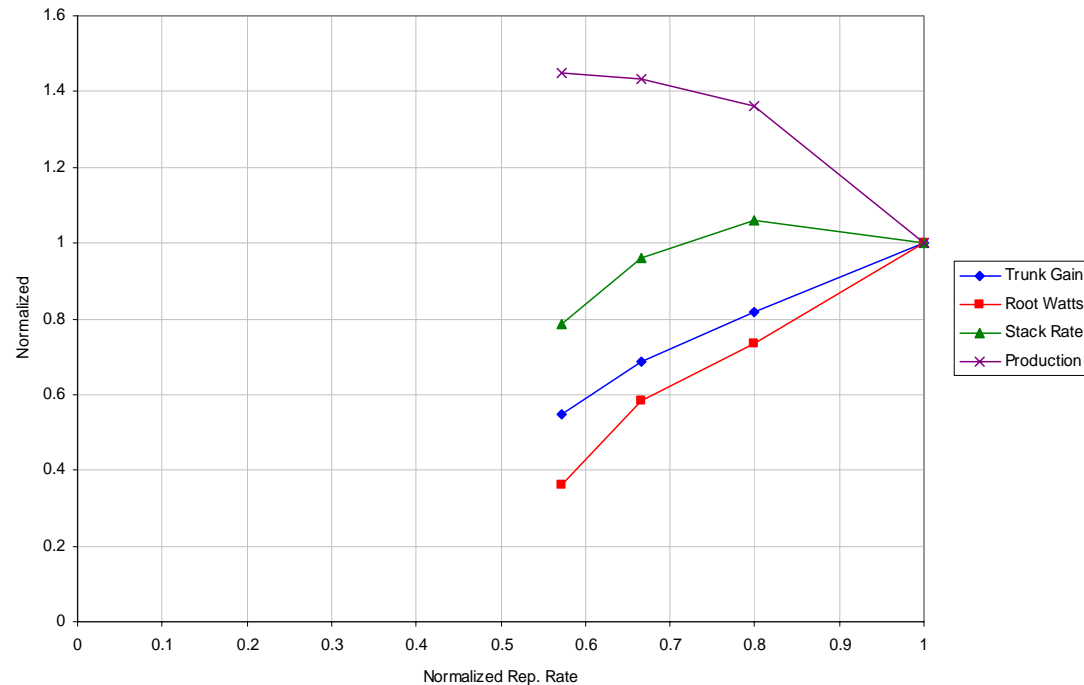
Cyan Trace with attenuator at 10.5 dB clears in 1.8 secs

Magenta Trace with attenuator at 4.5 dB clears in 1.2 secs

Variable Cycle Time While Varying Stacktail Gain

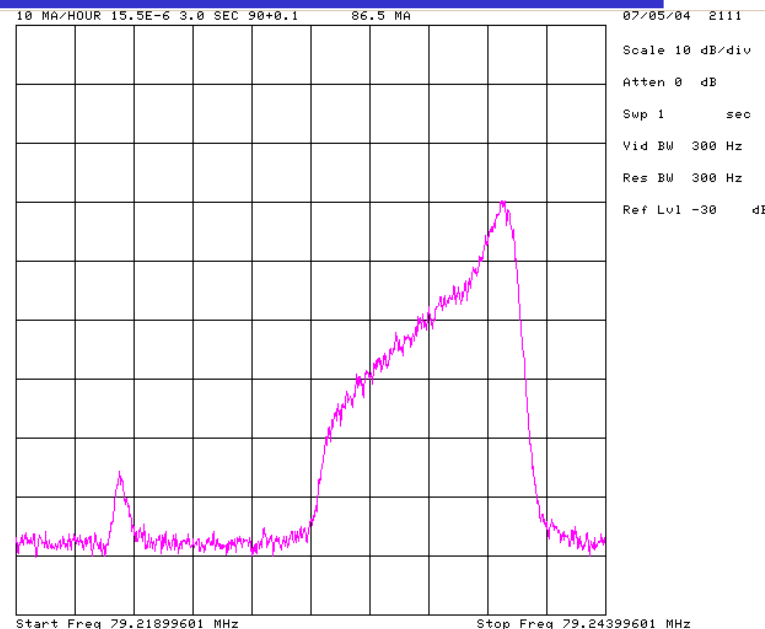
- With very small stacks, the cycle time was varied from 3.5 Secs. to 2.0 Secs. in steps of 0.5 Sec.
- At each step, the stacktail gain was adjusted so that the Stacktail profile exhibited a "hint" of back-streaming.
- Each data point was the average of ten 60 Sec. super-cycles
- The drop in production negates short cycle times.

Cycle time	StackTail Trunk Attenuator	Stacktail TWT Power	Stack Rate	Production
Secs.	dB	Watts	mA/hr	$\times 10^{-6}$
3.5	17.5	65	7.8	14.8
3	15.5	170	9.5	14.6
2.5	14	270	10.5	13.9
2	12.25	500	9.9	10.2



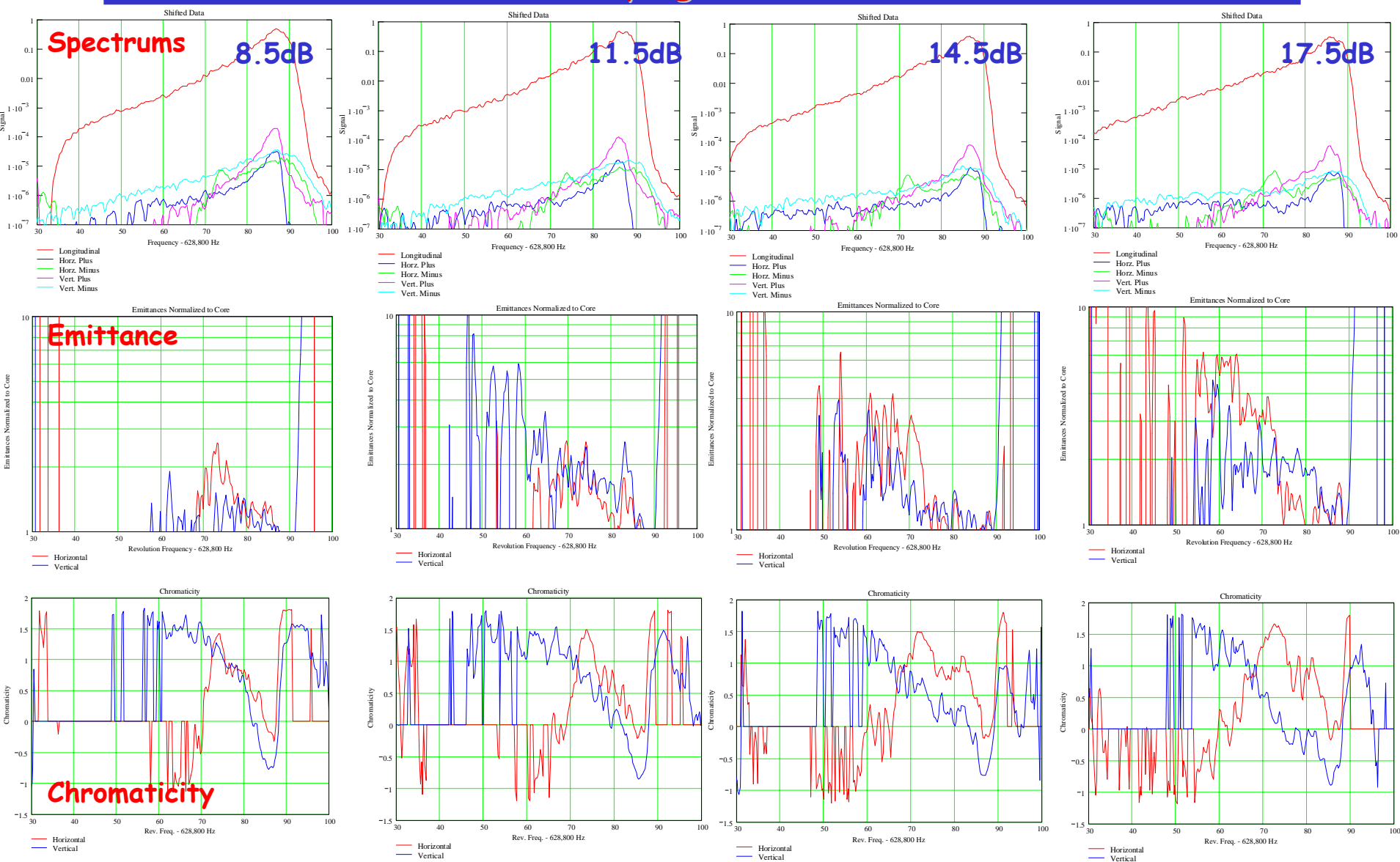
Constant Long Cycle Time While Varying Stacktail Gain

- Ran at a slow cycle time (3.5 secs)
- The lowest Stacktail gain was set for when the Stacktail profile had a "hint" of back-streaming
- Each data point was the average of ten 60 Sec. super-cycles
- Result: Small Stack Stack Rate does not seem to be a function of Stacktail Gain or Power
- Also measured transverse emittances through the Stacktail using Van der Meer's technique and found the emittances were fairly independent of Stacktail gain



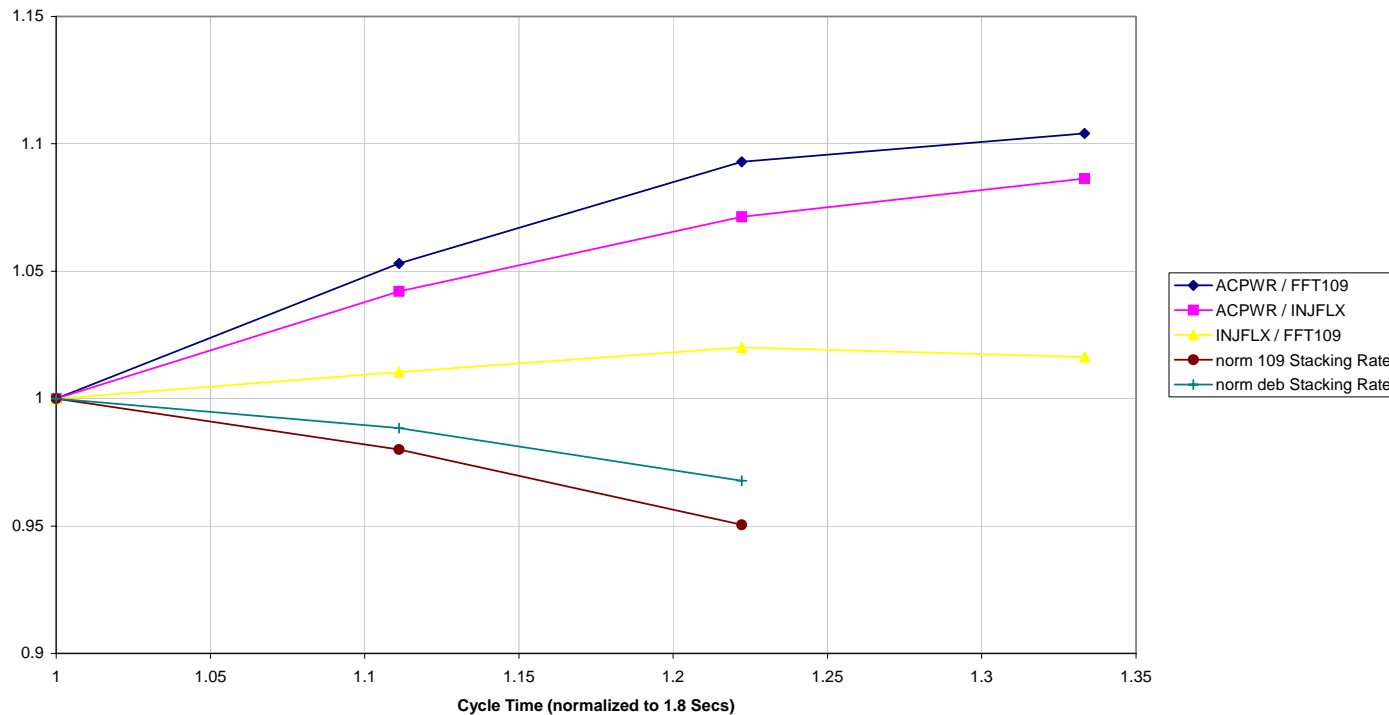
StackTail Trunk Attenuator	Stacktail TWT Power	Stack Rate	Production
dB	Watts	mA/hr	$\times 10^{-6}$
17.5	65	7.8	15
14.5	180	7.5	14.5
11.5	400	7.6	14.7
8.5	700	7.6	14.7

Measuring Stacktail Emittances with Constant Long Cycle Time While Varying Stacktail Gain



Zero Stack Measurements with Constant Stacktail Gain and Variable Cycle Time

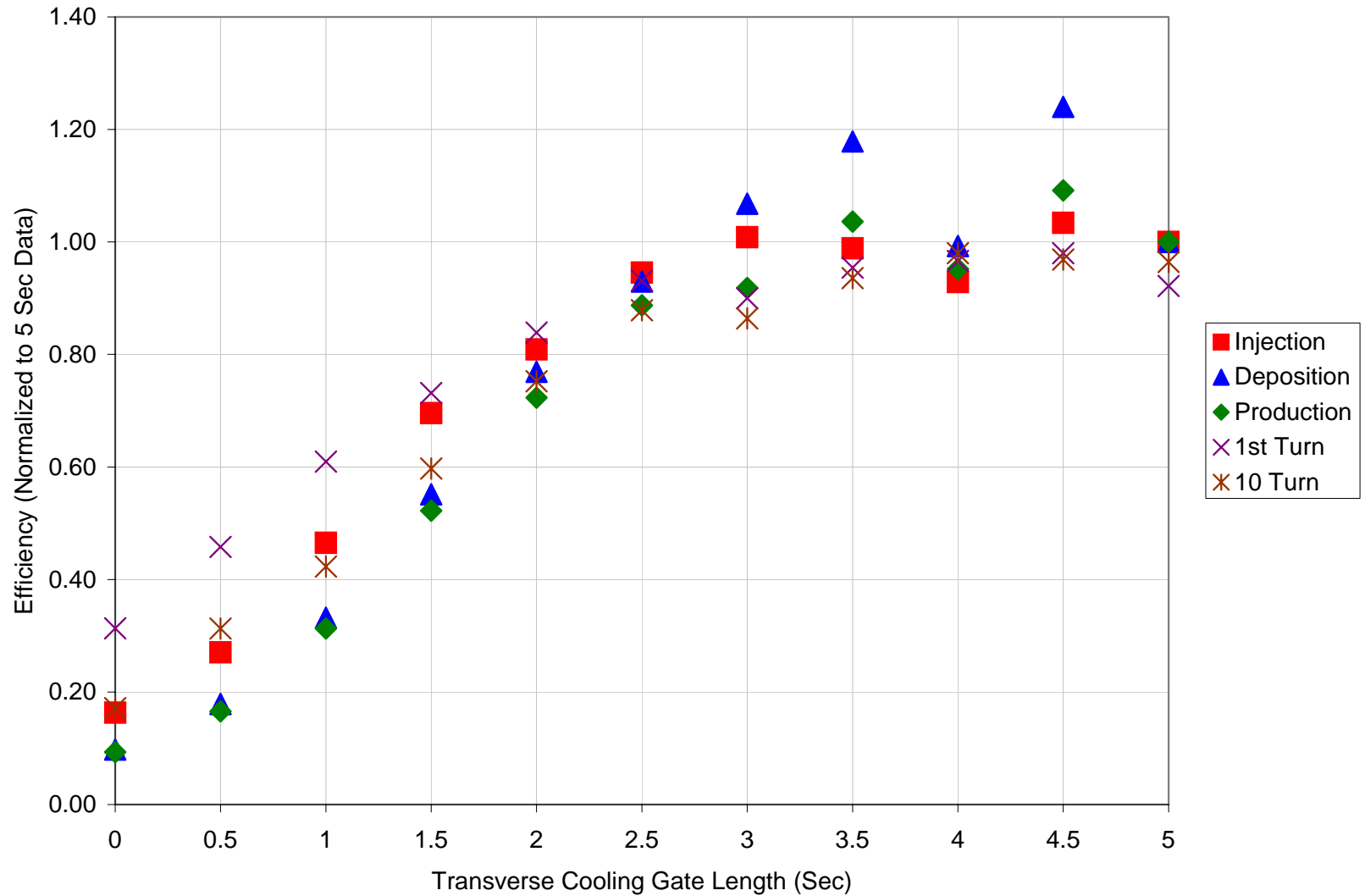
- Stacking measurements were taken with a fixed gain of 9 dB
- The stacking Rate falls 5% while the cycle time increases from 1.8 secs to 2.2 seconds
- If the amount of beam on the injection orbit was constant as a function of cycle time, the stacking rate should have fallen by 22% while the cycle time increases from 1.8 secs to 2.2 seconds
- Most of this discrepancy can be explained by the reduction in the fraction of beam making it into the Accumulator as a function of the cycle time



Pbar Production Efficiency vs Debuncher Cooling Time

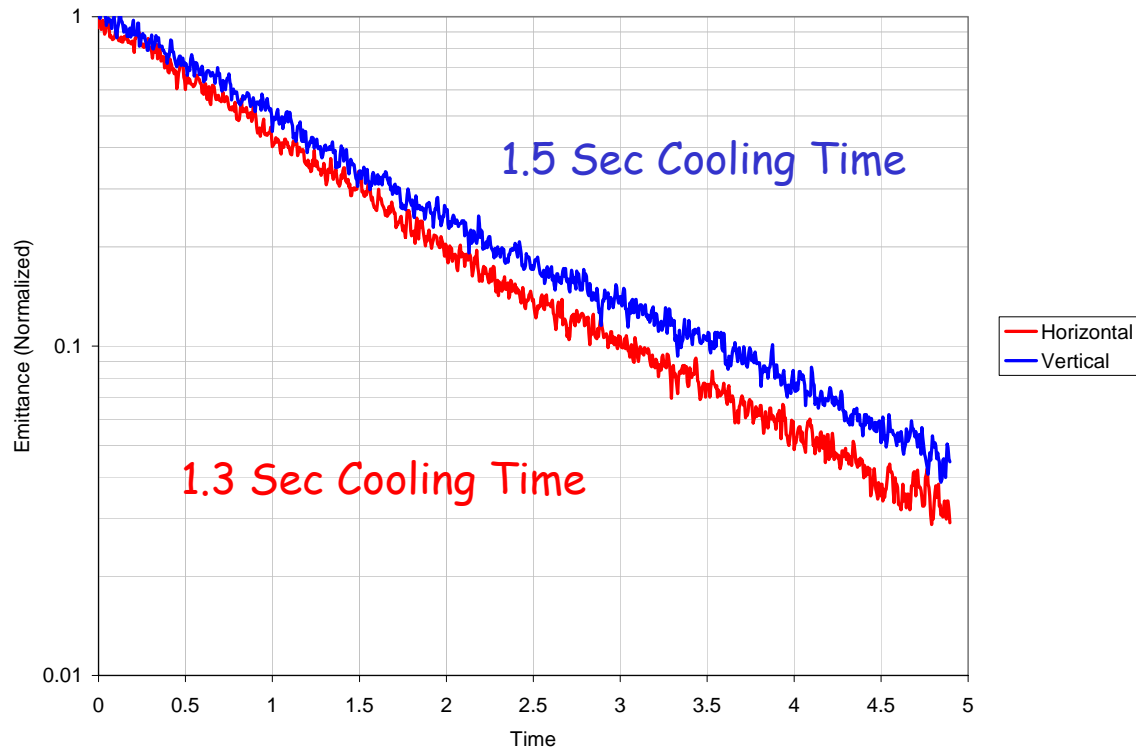
- To investigate if the reduction of beam injected into the Accumulator as a function of cycle time is due to Debuncher transverse cooling, beam transported to different stages of the Accumulator as a function of how long the Debuncher transverse cooling was left on was measured.
 - Done at small stacks
 - Done with a very long cycle time of 5 secs.
 - Low Stacktail and Debuncher Momentum cooling gain
 - Debuncher transverse cooling systems gate length was varied.
 - Injection and Deposition orbit efficiencies were measured using the Accumulator Longitudinal Schottky
 - Measurements were gated on only when Stacktail and ARF1 were gated off.
 - First and Tenth turn measurements were done by bunching the beam in the Debuncher at extraction from the Debuncher with DRF1 (53 MHz) and measuring the bunched beam intensity on the Accumulator Longitudinal Schottky
 - These measurements were done on different cycles than the measurements made with the longitudinal Schottky

Pbar Production Efficiency vs Debuncher Cooling Time



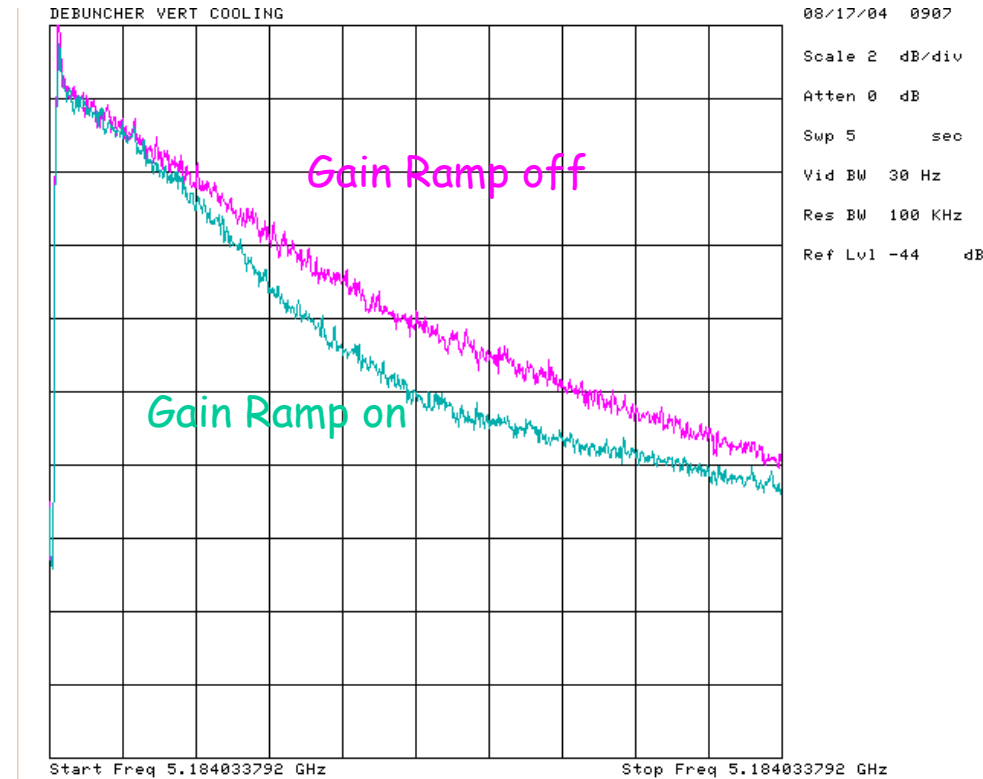
Debuncher Transverse Cooling

- Because of the low noise temperature and high impedance of the Debuncher transverse cooling pickups, the emittance as a function of time can be directly measured from the transverse cooling system schottky signals.
 - Measured over a single transverse sideband with a spectrum analyzer zero span mode.
 - Signal suppression is a small effect



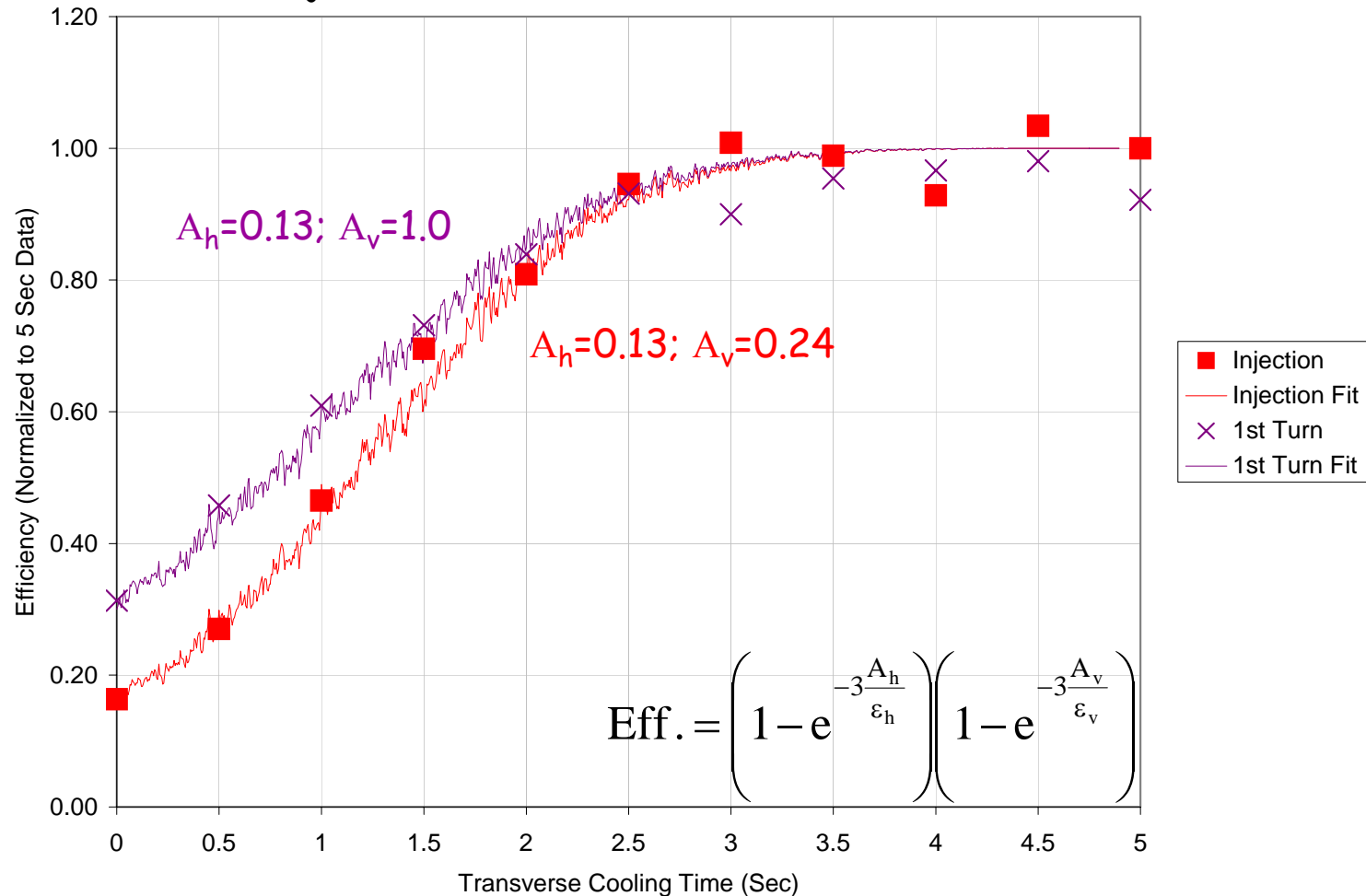
Debuncher Transverse Cooling Gain Ramping

- Transverse Schottky signal dominates the TWT power for Bands 1 & 2 of the Debuncher transverse cooling systems
 - Transverse Schottky signal is a noticeable component in Bands 3 & 4 as well
- Transverse gain ramping in which the transverse gain increases as the emittance decreases was implemented.
 - Systems well below optimum gain.
 - Gain ramps need more work



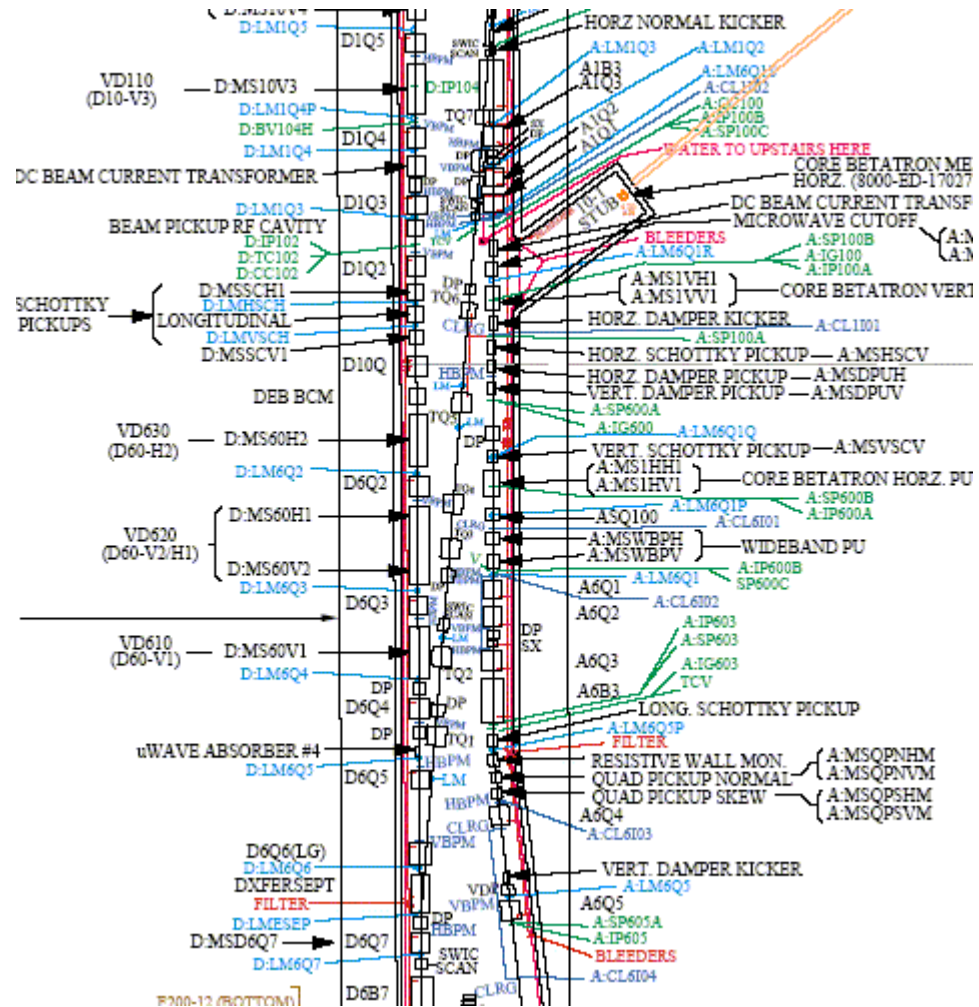
Debuncher Extraction - Accumulator Injection Aperture

- The production vs transverse cooling time measurements can be explained if there is an aperture restriction between Debuncher Extraction and Accumulator Injection

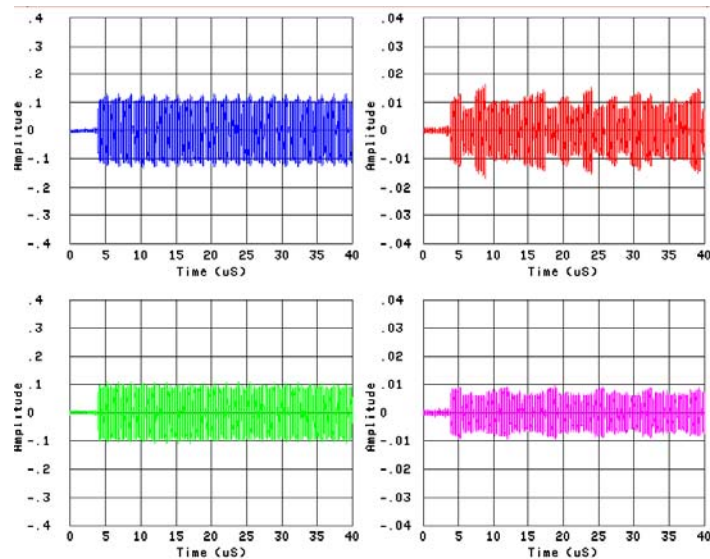


Reverse Proton Debuncher to Accumulator Transfer Line Instrumentation

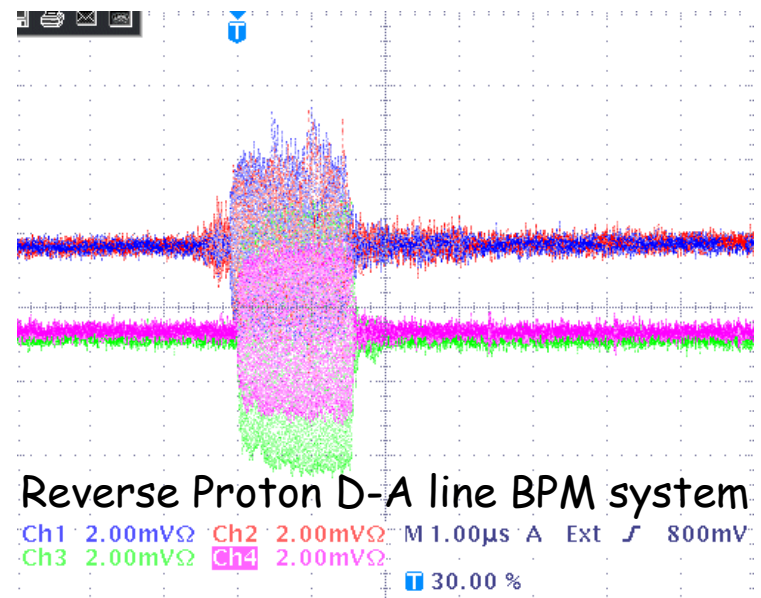
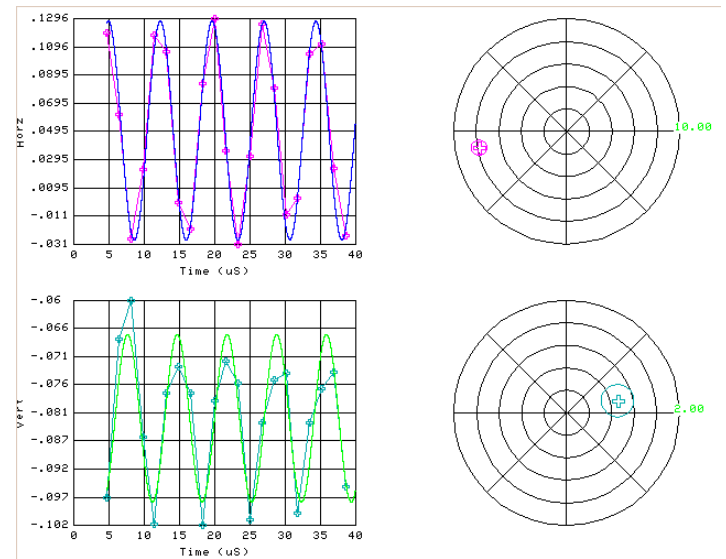
- To search for the the possible aperture restriction in the D-A Line we:
 - Developed a procedure for bunching reverse protons in the Accumulator with 53 MHz RF just before extraction from the Accumulator to the Debuncher
 - Instrumented 4 BPMs in the Accumulator, 7 BPMs in the D-A Line, and 1 BPM in the Debuncher to see the 53 MHz RF signal
 - Calibrated the cable loss for the above BPMs for an absolute intensity measurement
 - Developed a 53 MHz Reverse Proton TBT system in the Debuncher



Reverse Proton Debuncher to Accumulator Transfer Line Instrumentation



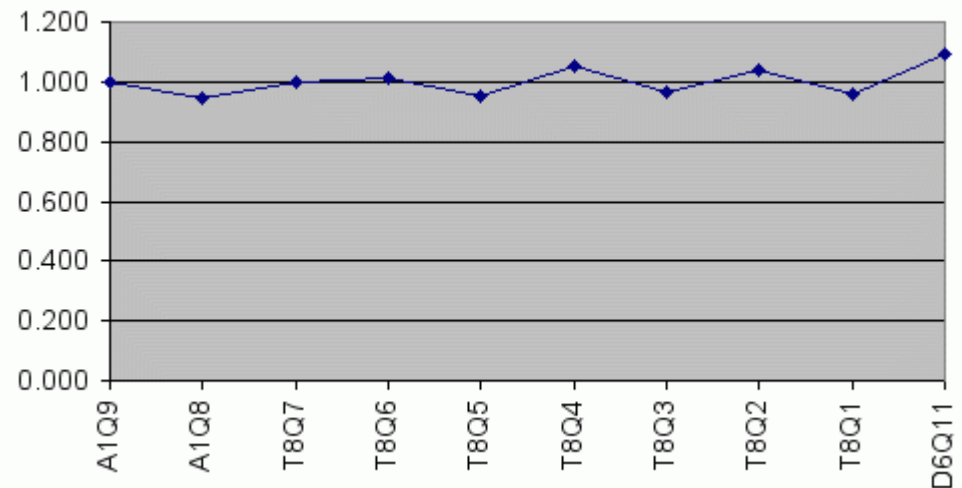
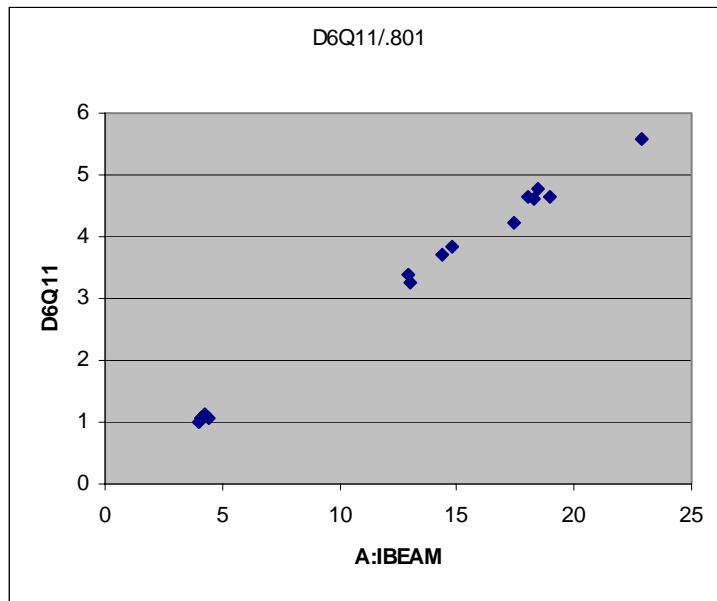
Reverse Proton TBT System



Reverse Proton D-A line BPM system

Reverse Proton D-A Transfer Line Studies

- We were unable to see any large intensity drop in intensity for reverse protons in the D-A line
 - The beam was blown up to the Accumulator aperture of 6π -mm-mrad before extracting from the Accumulator to the Debuncher
 - BPM intensity signal tracks beam current in the Accumulator

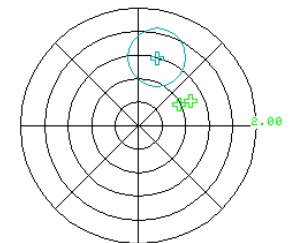
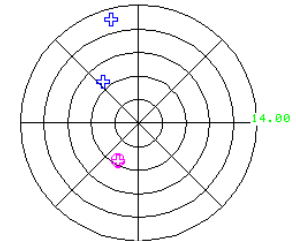
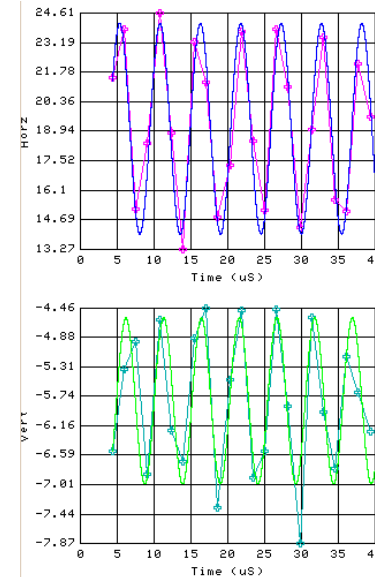
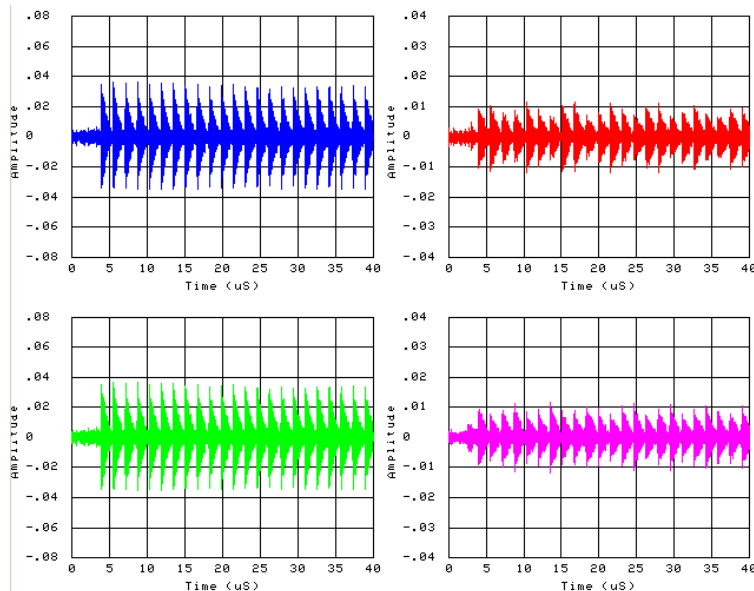
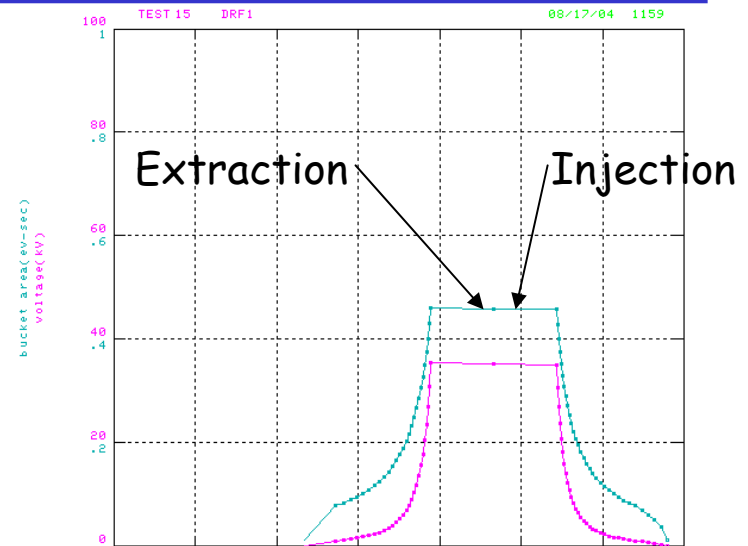


Possible Explanations for Reverse Proton BPM Studies and Forward Pbar Production Measurements

- The forward pbar trajectory is different from the reverse proton trajectory
 - Trajectories were not closed for either species
 - Reverse protons go from a small aperture to a big aperture - closure not as important
 - Forward pbars go from a larger aperture to small aperture - closure is much more important
 - Directional differences of kickers and timing
- The optics of the D-A line is not matched
 - Optics wrong on paper (i.e. the injection lattice of Accumulator is different than the lattice of the Accumulator on the central orbit, also sensitivity of optics to small errors)
 - There is something wrong with a component in the transfer line
- The measurements could be wrong.

TBT System for Pbar Injection into the Accumulator

- Needed to develop bunched beam at injection into the Accumulator
 - Used DRF1 to bunch beam at end of cycle in Debuncher by extending bunch rotation curve backwards in time
- Used 79 MHz Schottky to see transverse and longitudinal motion of the beam in Accumulator at 53 MHz
 - Resonant effect probably does not help that much
 - Long pickup and good pre-amps reason for seeing good bunched signal



Uses of the TBT System for Pbar Injection into the Accumulator

- Close pbar trajectory into Accumulator
 - Done during the last day of studies
 - Did not seem to effect efficiency much
 - Did not do a transverse cooling time scan
- Measure Quad Steering in the D/A line
 - Each quad in the D/A line is independently controlled
 - Measured a significant amount of steering in the middle of the line
 - Analysis ongoing
 - Will be used for beam-based alignment in the future
- Measure response matrix of D-A transfer line
 - Measure unperturbed trajectory by using quad shunts to measure steering in the D-A line
 - Place a trajectory perturbation at beginning of line and by using quad shunts to measure steering in the D-A line
 - Compare quad steering orbits
 - Initial data already taken - Analysis ongoing
- Measure TBT injection intensity into Accumulator (see slide 23)
 - Can also be used to tune DRF2 voltage slope in between barrier bucket

Conclusions

- The momentum spread extracted from the Debuncher into the Stacktail has been decreased by about 35% over the past year.
 - Future gains are possible but will be much smaller
 - Increase bandwidth of Debuncher momentum cooling system with equalizers
 - Optimize gain profile (each band at optimum gain) and gain ramping for Debuncher momentum cooling system.
 - Fix DRF2 voltage slope for rectangular phase space
 - Investigate feasibility of ramping γ_+ in Debuncher

Conclusions

- The present Stacktail system with the bandwidth as measured should be capable of handling a static flux of 29mA/hr
 - The upper end of the bandwidth should be restored with a correction to the BAW equalizer design
 - At small stacks, the present Stacktail system can clear the deposition orbit as fast as 1.2 seconds
 - At small stacks, increasing the Stacktail gain or power does not affect stacking
 - It also does not seem to affect the emittances in the Stacktail
 - The curves for the deposition RF system (ARF1) have been optimized but should include bunch tumbling to match the Stacktail Profile
 - Note in the future, that the present 2-4 GHz Accumulator Core Momentum Cooling system will have to be replaced with either the present or modified 4-8 GHz Accumulator Core Momentum Cooling system if the Accumulator is going to have to continue support large stacks.

Conclusions

- In the range of cycle times of interest, the amount of beam reaching the injection orbit of the Accumulator is proportional to how long the transverse cooling is on in the Debuncher.
 - Indicates an aperture problem in the D-A line.
 - The transverse cooling can be increased marginally by optimizing transverse gain ramping

D-A Line Plan of Work

- Plot the beam envelope against an accurate model of the D-A line aperture. (The D-A line model should go from kicker to kicker)
 - Assemble mechanical drawings of all components in the D/A line
 - Collect survey data of D-A line
 - Referenced to Debuncher Extraction and Accumulator Injection
 - Double check survey data against "common" sense measurements
 - Develop an accurate lattice model of Debuncher - D/A line - Accumulator Injection orbit
 - Check these models with beam based measurements
- Open up the D-A line for visual inspection during the shutdown
- Install a Debuncher Extraction Ramped Bump
 - Optimizes maximum closed orbit aperture at injection
 - Optimizes extraction channel aperture
- Build a forward Pbar BPM system in the D-A line